Emerging Needs in Japan for Health Monitoring Technologies in Civil and Building Structures

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ABSTRACT

The needs for health monitoring systems are recently emerging in Japan for many industrial structures including civil and building structures. The trend has been accelerated after the 1995 Hyogo-Ken Nanbu Earthquake in which the damages of beam-column joints in many steel buildings were found only after conducting elaborate one-by-one eye-inspections. Difficulty to evaluate the damages in pile foundations was also reminded by this event. In addition, recognition of the importance of renovation and rehabilitation markets associated with huge accumulation of infrastructures and buildings during the booming era is demanding urgent development of sophisticated health monitoring systems for minimizing costs and time by obtaining proper damage status. Two national projects launched by the Ministry of International Trade and Industries and the Ministry of Construction indeed reflect the strong needs for the technology. Noteworthy and important advances in fiber optic sensors and a network technology that will play an important role are briefly explained.

OVERVIEW

A health monitoring system starts getting strong attentions in Japan after the 1995 Hyogo-Ken Nanbu (Kobe) Earthquake in which more than 6,000 people were killed and 40,000 buildings were destroyed. As was the case after the 1994 Northridge Earthquake, many steel buildings suffered sever damages mainly at their beam-column joints. It was a surprising fact that the damages were not found until removing fire-protection coatings on beam-column joints. In most cases, it was not possible to find the correct degree of the damages by a simple eye-inspection of the structure surface because there were no major visible damages. This fact prompted strong demands in nondestructive assessment systems for steel buildings without removing fire-protection materials.

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Another key issue raised at the 1995 Hyogo-Ken Nanbu (Kobe) Earthquake was the difficulty to find and quantify damages in piles and foundations of a building. If the building were inclined or tilted, it would be rather easy to specify the cause of the damage. However, as was the case for beam-column joints in steel structures, a simple eye-inspection could not identify the damages in piles and foundations. Even when a damage was identified to be in pile systems, it was necessary to excavate soils under the foundation for accurate assessment. The cost for the assessment involving soil excavation is very expensive. Thus, an efficient health monitoring system for piles and foundations is sought by many research groups.

In the course of development for health monitoring systems for steel structures, piles an others, it was found that the current sensor and network technologies had certain limitations for proper assessment. For example, nondestructive damage assessment of beam-column joints in a tall steel building is very difficult without removing coating materials for fire-protection. Evaluation of embedded piles is further difficult since excavation of foundation soil is necessary for installing sensors. Though several nondestructive methods were proposed, no method could satisfy all the requirements for correct assessment of damages. They are, in most cases, only applicable to detect local damages under the condition that engineers can have a proper access to the target location with their equipment. Even if it is possible to install exciters and sensors to the locations of interests. However, the cost required is prohibitively expensive. Under these circumstances, fiber optic sensors are gathering keen attentions due to their durability, electromagnetic immunity, versatility, multiplexing capability and possibly low production costs.

In addition to the beam-column steel joints and piles, damper devices for structural control are becoming sources of needs for health monitoring systems. Typical damper devices currently used in Japan are depicted in Figure 1. The number of devices installed into a tall steel building can easily exceed one hundred. However, the inspection practice depends solely on eye-inspections so that a certain number of wall panels covering damper devices have to be removed when the building is hit by a large earthquake. This inspection work will be tedious and time-consuming. Furthermore, structural engineers will not be easily available because they will be very busy after the large earthquake due to first-aid assignments. If an affordable monitoring system is available for damper devices, such a nightmare will disappear.

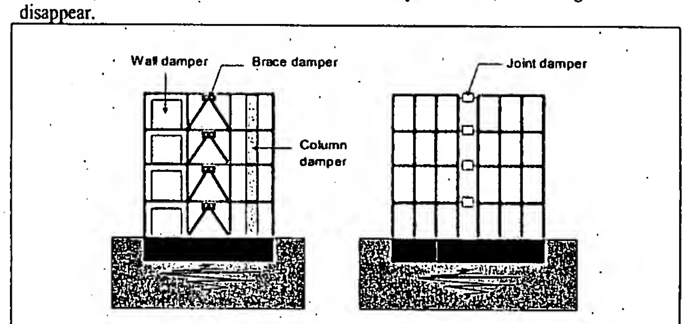

FIGURE 1. DAMPER DEVICES FOR STRUCTURAL CONTROL

The government investment in civil infrastructures is at its highest level to compensate the reduction in private investment in plant and equipment. However, this level of government investment will not last for many years due to financial difficulties. In addition, the ratio of the government investment to the GDP is extremely high in Japan compared with Europe and the U. S. It is natural to forecast that the investment in new buildings and infrastructures will keep declining for coming years. On the contrary, renovation and rehabilitation of existing buildings and infrastructures are anticipated to grow very fast. This is also the reason why the needs for health monitoring systems have become evident. A health monitoring system is expected to be helpful for minimizing maintenance costs. The average age of civil and building structures is younger than those in Europe or the U. S. Therefore, the Japanese people were recently aware of the growing market.

An existing market for monitoring systems is for construction sites. At urban regions, it is common to have many underground structures in the construction sites. Damaging those structures will result in huge economical loss. Therefore, careful monitoring should be conducted by a company that is in charge of construction. Many sensors such as displacement sensors, pressure sensors and strain sensors are deployed depending on the specified requirements. The system is needed to survive for a limited period by the time of completion so that the required life for sensors is rather short. In addition, the warning criteria are straightforward and simple for construction management so that no sophisticated system identification techniques are needed.

The life-cycle of a building can be divided into four phases as shown in Figure 2. Clear demands exist at "Construction" and "Emergency" phases. Additional demands are increasing also for "In-use" and "Renovation" phases due to introduction of the performance-based design. The performance-based design will allow a designer more freedom and flexibility for designing but have to face increased liability. A health monitoring system is expected to be the most promising means to assure the performance and to protect designers. In "Renovation" phase, the data obtained from the health monitoring system will be useful for making an optimum scenario for renovation to minimize the cost and time. For a construction company, the health monitoring system is even more attractive to catch signals to identify possible customers for renovation or new constructions.

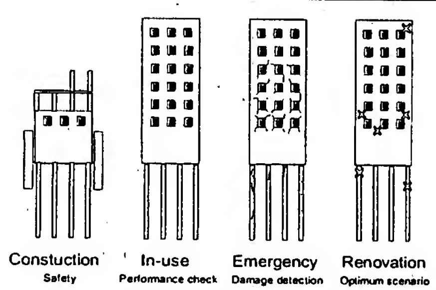

FIGURE 2. FOUR LIFE-CYCLE PHASES OF BUILDING

FIVE-YEAR NATIONAL PROJECTS

Reflecting the emerging needs for health monitoring technologies, two important national projects were launched in the fiscal year 1998. Both projects will last for five years and involve many industries. They are briefly explained below.

MITI university-industry collaborative program on "Smart material/structure system"

The Japanese government introduced a new scheme for university-industry collaboration projects in 1998. This scheme emphasizes clear leadership of universities for collaboration. All researchers including those from industries should work at research centers established on university campuses. The five-year project "Smart material/structure system" is one of four projects approved in the fiscal year 1998. The project is sponsored by the Ministry of International Trade and Industries (MITI) through the New Energy and Industrial Technology Development Organization (NEDO). The annual budget is 900million Japanese yens or 7.5 million in US dollars.

The project is being conducted by four research groups:
(1) Health monitoring,
(2) Smart manufacturing,
(3) Active/adaptive structures, and
(4) Actuator materials development.

The first research group on "health monitoring" is lead by Prof. N. Takeda at the University of Tokyo. The industries participating in this research group are: MELCO, Aerospaciale, Toray, JFCC, MHI, KHI, FHI, Hitachi, Hitachi Cable and Shimizu. The target structures are satellites, airplanes, magnetically levitated trains, tall buildings and infrastructures.

RESEARCH TOPICS FOR HEALTH MONITORING GROUP

The research topics currently being pursued by the health monitoring group are listed below [1]:

(1) Development of high-performance sensor system technology
- (a) Development of optical fiber sensor (OFS) technology
  - Development of strain, temperature, load detection technology using OFS
    - Fabry-Perot, Bragg grating, BOTDR
  - Development of damage detection systems using OFS
  - Development of assembly technology of OFS-embedded composites
- (b) Development of novel OFS technology
  - Development of small-diameter OFS - less than 50 μm
  - Improvement of OFS coating
- (c) Development of damage suppression composite systems using shape memory alloy fibers/films
  - Suppression of transverse crack initiation in composite laminates
  - Suppression of transverse crack growth

- Suppression of delamination initiation and growth

(d) Development of smart patch sensors with maximum strain memory
- Development of smart hybrid patch sensors (SHPS) with various carbon fibers
- Improvement of fiber coating and matrix for SHPS
- Development of SHPS with self-diagnosis and alarm functions

(e) Development of damage detection systems of transparent composites using light transmission and reflection

(f) Development of integrated high-resolution AE sensor systems

(2) Development of self-diagnosis and damage suppression systems for structural integrity

(a) Correlation between sensor outputs and mechanical/physical values

(b) Correlation between sensor outputs and damage mechanisms

(c) Development of self-diagnosis and damage suppression systems

(3) Development of implementation technology for model smart structures

(a) CFRP airframe structure systems
- Stiffened panels with OFS - static and repeated loadings
- Stiffened panels with OFS - impact loadings
- Stiffened panels with shape memory fibers/films
- Box-beam or stiffened cylindrical shells
- Pressure vessels and cryogenic tanks

(b) Satellite structure components

(c) Load-supporting structures of super high-speed trains

(d) Tall buildings, infrastructures

EXAMPLE CONCEPT

A smart composite system currently being investigated is shown in Figure 3. The system includes shape-memory alloy fibers to decrease residual tensile thermal strains in transverse piles and to decrease the crack opening displacement at crack tips. This capability will result in suppressing the growth of delamination in the composite system.

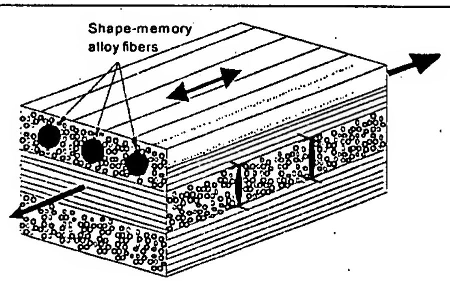

FIGURE 3. COMPITE SYSTEM WITH SHAPE-MEMORY ALLOY FIBERS

MOC five-year project on "Smart structure systems"

The Building Research Institute (BRI) at the Ministry of Construction (MOC) launched a five-year government-industry collaboration project on "Smart structure systems" [2] in 1998. The purpose of the project is to develop smart structure systems for buildings. A smart structure system is defined as a structure which appropriately responds to the change of external disturbance to maintain its functions and to provide reliable safety. In a long range, such a capability may result in extending the building life-span. Participants from industries include the Building Contractors Association, Housing and Urban Development Corporation, Building Center of Japan and several materials and sensors industries. In the project, the health monitoring system will play an important role to realize the smart structure system.

The project has a U. S. counterpart supported by the National Science Foundation. The steering committee of the U. S. organization is chaired by Prof. R. Frosch and Prof. M. Sozen at Purdue University. Two workshops were held in the U. S. with several guests from the Japanese counterpart.

RESEARCH TOPICS

Three sub-committees corresponding to three research topics were formed. The research topics are summarized below:

(1) Smart structure system concept (chair; Prof. A. Wada, Tokyo Institute of Technology)
- Definition and categorization of smart structure system
- Summary of the required performance of smart materials or devices to realize the smart structure system
- Performance verification of proposed smart structure system concept by computer simulation and experiments
- Establishment of guideline for the performance evaluation of smart structure system

(2) Sensing and monitoring (chair; Prof. Y. Kitagawa, Hiroshima University)
- Structural health monitoring system
- Structural performance evaluation system
- Information system with sensors

(3) Effectors (chair; Prof. T. Fujita, the University of Tokyo)
- Embedded smart functions such as processors, sensors and/or actuators
- Improved performance (strength, ductility, usability, cost, etc.)

The research activities by the sub-committees are coordinated by a technical coordinating committee chaired by Prof. S. Otani, the University of Tokyo. The major funding sources are the Japanese government and industries.

In the fiscal year 1998, the basic framework of the project was made. In the following years starting in the fiscal year 1999, several working groups consisting of researchers from government institutes, universities and industries are going to be formed to pursue many research targets effectively.

RECENT ADVANCES IN OPTICAL FIBER SENSORS

Optical fiber sensors have been long considered to be the most promising candidates for sensors in a health monitoring system. Though many optical fiber sensors for structural applications have been developed, a few of them have truly become feasible for practical applications. Recently, noticeable advances in optical fiber sensors were reported in Japan.

Optical fiber sensor for concrete structures

The optical time domain reflectometry (OTDR) is commonly used in the communication industry. It can be considered as a one-dimensional guided radar as shown in Figure 4. This method utilizes the scattered lights in fiber cores due to series of input light pulses. Some components of input lights are scattered back due to reflectors, bending cores and others. The time delay of the scattered lights determines the distance between the source and the target point. The physical characteristics of the scattered lights can be associated with some physical response of the fiber at the point where the light was scattered.

Rayleigh, Raman and Brillouin scattering are commonly known phenomena. The Brillouin scattering reflects the smallest power among these three scattering phenomena and was found to be sensitive to both strain and thermal response of the fiber core. However, the scattering energy is so small so that it had been difficult to discriminate the Brillouin scattering component from noises. The Brillouin OTDR (BOTDR) recently developed by a team of NTT reached a feasible performance level to be used in civil engineering field [3]. Although it is not realistic to replace conventional strain gauges by the BOTDR sensors, capability of distributed sensing over a large distance is very attractive for certain applications.

NTT and Shimizu Corp. recently developed an optical fiber sensor which can be embedded into concrete structure for use by the BOTDR [4]. Their sensor can withstand the force due to pouring concrete and can survive when cracks are developed in the concrete. The structure of the optical fiber sensor for concrete structures is schematically shown in Figure 5. The diameter of the sensor is about 2 mm so that excellent handling capability is achieved. This sensor used with the BOTDR could measure accurate deformation and strain over a long distance. This capability is extremely useful for applying them to long and large infrastructures.

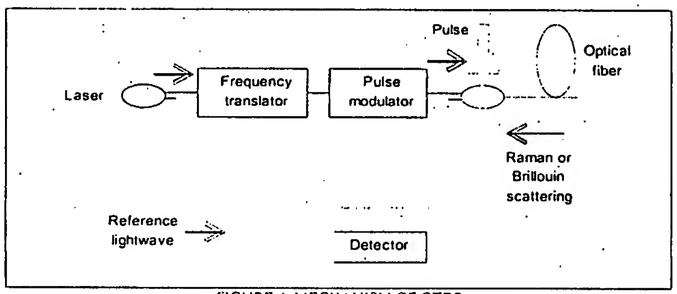

FIGURE 4. MECHANISM OF OTDR

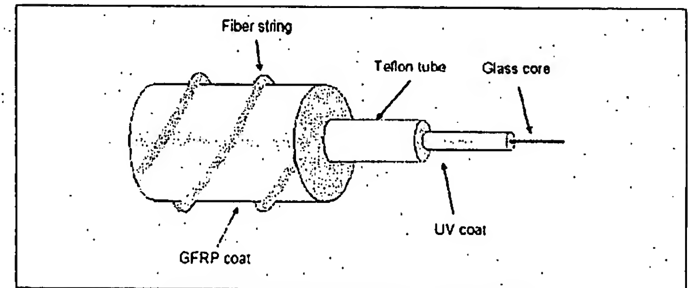

FIGURE 5. STRUCTURE OF OPTICAL FIBER SENSOR

Application of Raman OTDR for measuring temperature

Raman OTDR (ROTDR) sensors are currently available on the market. However, it was the first time to use communication fiber optic cables to measure temperature in the curing concrete slab of an in-ground tank for liquefied natural gas [5]. The diameter of the slab is about 70m. The depth of the slab is more than 10m. Due to the large volume of concrete, curing temperatures should be always measured to ensure designed performance of the concrete. Major reasons to employ the ROTDR were:

- A single optical fiber covers many measuring points so that the damage to the slab structure is negligible.
- Installation of sensor fibers requires less time and cost compared to conventional sensors.
- The number of measuring points can be 2-digits more than the conventional sensors with the same installation cost.

The installation layout of the ROTDR is presented in Figure 6. The accuracy of the sensor was verified by comparing with conventional sensors at certain points. The total length of the optical fibers exceeded 2 km. Therefore, the number of measuring points was more than 2,000. This large number of measuring points allowed us to employ a more elaborate control of curing processes. The diameter of the fiber cable is 12.5mm. A single cable can case six fibers. The mass of the cable is only 150kg per km. This light weight helped cut the installation time and cost. The fiber cable used here was mass-produced for communication industries so that the cost of the cable is fairly low.

The ROTDR sensor is considered to be more promising for permanent monitoring of soil temperature after completion of the in-ground tank. The liquefied natural gas should be kept at a very low temperature so that the soil deposits surrounding the tank will become frozen. If no heating control is made for the soils, the tank will be eventually floated and fractured. To avoid this catastrophic event, heating pipes are embedded in the surrounding soils to regulate the soil temperature. The thickness of the frozen soils is thus limited within a certain range. The ROTDR is ideal as a temperature sensor for this purpose. In addition, there is no danger to ignite a fire.

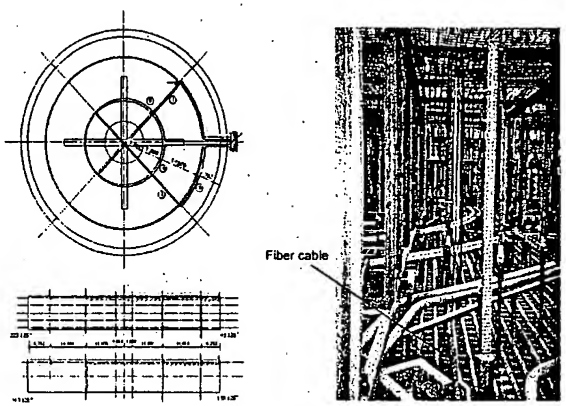

FIGURE 6. FIBER OPTIC SENSOR FOR IN-GROUND TANK

Optical accelerometer

Accelerometers are the key components in a health monitoring system for civil and building structures especially for detecting damages due to earthquakes and wind loads. Optical accelerometers have many advantages over conventional electrical accelerometers such as their immunity to electromagnetic interference and their capability to transmit signals over long distance without any additional amplifiers. There exist several systems using micro-bending [6], optical diodes and a vibration wire [7]. The latter system was later improved to use an LC circuit instead of a vibration wire [8]. However they are not yet widely used due to their cost and other reasons.

Shimizu Corp. and Tokyo Sokushin Inc. recently announced their new optical accelerometer. The configuration of the sensor is depicted in Figure 7. The structure is simple. A fiber Bragg grating sensor is used to detect the strain induced by the vibration of weight. Therefore, the acceleration of weight can be obtained by detecting the change in the Bragg wavelength. Due to this simplicity, the production cost can be very low. The same system concept is applicable to displacement, pressure and force sensors.

The important advantage of their system is multiplexing capability. Though the number of sensors which can be multiplexed depends on their dynamic range, multiplexing up to ten sensors is considered to be feasible for most applications. Different types of sensors can be multiplexed on the same fiber cable. For example, if an accelerometer and several pressure sensors are multiplexed, a liquefaction sensor can be set up using only one interrogation system. This capability reduces the system and installation cost, drastically.

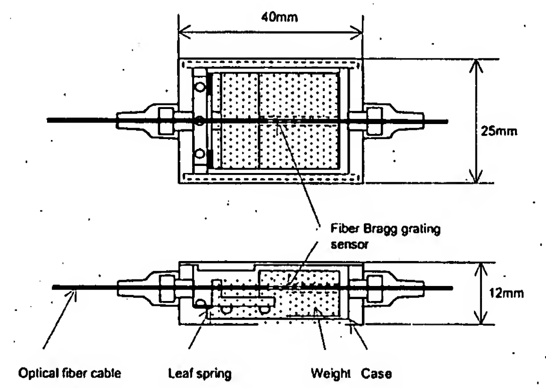

FIGURE 7. CONFIGURATION OF OPTICAL ACCELEROMETER

MONITORING SYSTEM FOR CONSTRUCTION MANAGEMENT USING WEB SERVER

A health monitoring system may consist of variety of sensors that are not only advanced sensors but also conventional sensors. In some cases, measurement should be done by humans. Each group of sensors may have an independent interrogation system which is capable to hook to a network. However, in a practical situation at present, data from the sensors are gathered in many forms such as floppy disks, networks or even typing. Therefore, processing all data obtained in several forms is an extremely tedious task.

At a large construction site involving ground excavation in the urban region in Japan, monitoring of ground deformation and associated physical values is mandatory during construction for protecting lifelines and/or subway tunnels. For each monitoring item, an engineering company is usually assigned. The engineering company is responsible for data acquisition but is not required to transmit the recorded data to the site network. Interpretation of the acquired data is made by site engineers or consultants using printed data prepared by the engineering company. Therefore, it takes time to make proper judgements.

To resolve such a situation, a monitoring system was developed by Shimizu Corp. [9]. The configuration of the monitoring system is depicted in Figure 8. The server utilizes the HTTP protocol to communicate with client PCs. The data acquired by engineering companies are transferred to the server using a simple protocol called NFS. All measured data are automatically stored in the monitoring server. Site engineers, designers and consultants are now able to access any data from their PCs. The current and previous conditions can be easily monitored through dynamically generated graphs, tables and condition maps. The data can be downloaded from the server under the condition that the client PC is connected to

the network and that the user has an access privilege. The system has been installed in many construction sites for building and civil structures. Typical view windows are shown in Figure 9. The colors such as red, yellow and green are used to tell the warning level at each measuring location. For example, when a red color is lit, the construction works should be immediately stopped. A single click of the red point will show what is happening at the measuring point. Most of the server functions are achieved by JAVA applets so that portability of the system is excellent.

The system explained here is for construction management. However, the same system configuration can be applied to a health monitoring system for other purposes. By interfacing the system by the web server, the data formats are automatically converted into a common format. What we need to do is to install identification tools and condition assessment tools into the server using the data stored in the common format. The major difficulty remained is associated with networking. No standard wireless networking system is available for a construction site. However, many wireless systems are now being commercialized so that this difficulty will be resolved very soon.

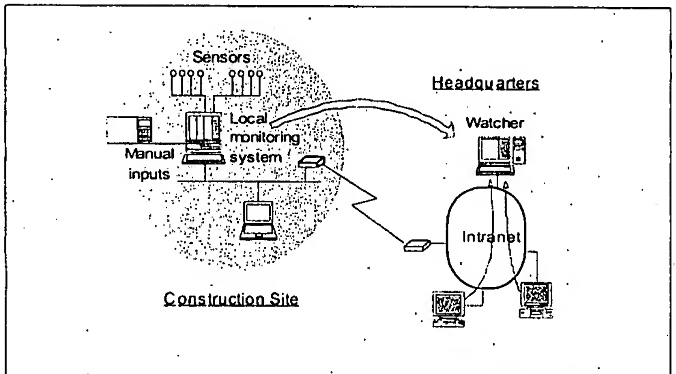

FIGURE 8. MONITORING SYSTEM FOR CONSTRUCTION MANAGEMENT

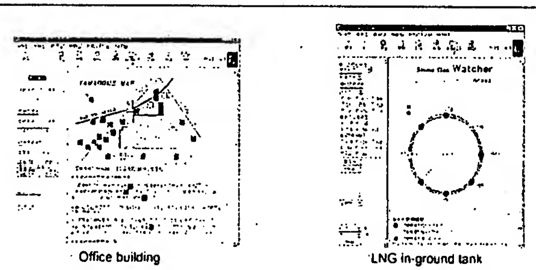

FIGURE 9. STATUS WINDOWS

CONCLUDING REMARKS

The needs for health monitoring systems are recently emerging in Japan. The application targets include civil infrastructures, buildings, satellites, airplanes, maglev trains and so on. The trend has become evident after the 1995 Hyogo-Ken Nanbu Earthquake in which the damages of beam-column joints in many steel buildings were found only after conducting elaborate one-by-one eye-inspections of beam-column joints. The difficulty in quantifying the damages of pile foundations was also recognized. In addition, under the saturating market condition for new constructions, the importance of renovation and rehabilitation markets for infrastructures and buildings is now evident. This situation is also enhancing the urgent needs in development of sophisticated health monitoring systems as tools to minimize costs and time by through the knowledge of correct damage status.

Two national projects launched by the Ministry of International Trade and Industries and the Ministry of Construction will attract many researchers and help improve the health monitoring technologies quickly. Noteworthy and important advances in fiber optic sensors and a network technology that were recently released in Japan will provide attractive means for developing a future generation of the health monitoring system.

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